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The Mg II emission in a sample of regular-period RS CVn systems

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Summary. We have studied a sample of ten RS CVn systems by means of IUE high resolution long wavelength spectra. A general trend toward decreasing chromospheric activity (R_{hk}) for slower rotating stars has been found.

Considering the R_{hk} values and their relation with structural parameters ($T_{\rm eff}, \log g, \log P_{\rm rot}$) we suggest that there are two possible different activity levels. The less active systems have R_{hk} chromospheric activity levels similar to the single cool stars showing the same general trend. A relation between R_{hk} and the inverse Rossby number has been obtained, in which the RS CVn stars fill the gap found by Rucinski between W UMa and the main-sequence stars.

Key words: RS CVn binaries – chromospheric activity – Mg II emission

1. Introduction

The RS CVn stars are binaries with orbital periods of 1–14 days. They constitute a well defined class of objects with strong Ca II H and K line emission and a wave-like distortion in the optical light curve is detected outside of eclipse. These characteristics can be explained by means of the generally accepted starspot model in which magnetic fields are presumed to be responsible for the dark zones in the photosphere and the greatly exaggerated but solar-like activity occurring in the chromosphere and corona. Usually these systems consist of a non-variable primary star, close to main-sequence, and a cooler component, normally a K0 V–IV star, which shows an unusual enhancement of its chromospheric and transition region lines.

In spite of the large space density of known RS CVn systems and the increasing abundance of observations, a comprehensive understanding of the phenomenon has not been achieved. Part of the problem is due to binary nature of the stars in that many are double-lined systems of similar luminosity and spectra are difficult to interpret. A greater problem is obtaining adequate phase and time coverage. Finally, it is difficult to acquire simultaneous photometric and spectroscopic data over a wide spectral base line.

We intend to study the appearance of the emission features in the *h* and *k* lines of Mg II ($\lambda\lambda$ 2802.7 Å and 2795.5 Å respectively) in a large sample of RS CVn stars from IUE images and determine the possible presence of two emission lines, one from each component.

We look for a correlation between this chromospheric activity indicator (the Mg II emission core) and the orbital period, temperature or gravity. For normal lower main-sequence stars such a correlation has been reported for Ca II and Mg II chromospheric activity indicators (Noyes et al., 1984; Hartmann et al., 1984).

2. Observation of the Mg II emission

In Table 1 are listed all analysed systems and their physical parameters (period, temperature, radius, distance, mass and Julian date of conjunction). Rotational periods are assumed equal to the orbital periods, since the RS CVn stars have quasi-synchronous rotation periods. Typical difference between orbital and rotational periods is 0.1% for these stars. The phases were computed from ephemerides listed in this Table.

All systems listed in Table 1 are well known RS CVn binaries:

– 13 Cet is a triple system consisting of a short period visual binary of which the primary is an RS CVn spectroscopic binary. Gatewood and Sofia (1976) suggested that 13 Cet is an over-luminous system.

– UX Ari is a non-eclipsing RS CVn star and one of the brightest member of this class. To explain the strongest emission bursts of UX Ari and other RS CVn systems, Simon et al. (1980) have suggested a magnetic connection by a tube flux between the stars. This model allows a temporary mass exchange that causes large line asymmetries, as observed in this system.

– 54 Cam consist of two stars of similar masses and similar luminosities ($L_2/L_1 = 0.7$) and is a double-lined spectroscopic binary. Eaton et al. (1981) have proposed that 54 Cam would hold magnetic tube connection phenomena with mass exchange, analogous to UX Ari. They also suggested that the mass exchange is corroborated by the fact that 54 Cam is a radio source and is favoured by the larger difference between orbital and rotational periods. However Walter et al. (1983) showed that the loops in AR Lac ($P = 2^d$) at quiescence do not connect the stars. Hence the interacting tube fluxes are highly unlikely in a fairly wide binary like 54 Cam ($P = 11^d$).

– TY Pyx is a RS CVn system with two peculiarities: a) the spectral type of the secondary star is earlier than usual and b) the secondary star radius is 1.68 $R_\odot$, while the typical radius for RS CVn secondaries is $>2.5\,R_\odot$. Furthermore, the two components of this binary are very similar stars, with comparable mass,

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Table 1. Stellar parameters

Name	Spectral type (hot/cool)	Period (days)	Temperature (K)	R ($R_\odot$)	D (pc)	M ($M_\odot$)	Conjunction date (2400000+)
13 Cet	F8 V	2.0819	/4900[g]		17[k]	0.44/0.24	24549.576
UX Ari	G5 V/K0 IV	6.4379	5770/5000[g]		50		40133.766
54 Cam	F8 V	11.0764	/5860[g]	/1.2	38		22379.517
TY Pyx	G2 IV/G5 IV[a]	3.1986	5400/5340[a]	1.59/1.68[a]	50[a]	1.22/1.20[a]	43187.229
RS Cvn	F4 IV/K0 IV	4.7979	6500/4685[h]	1.92/4.01[h]	145	1.33/1.39[h]	42861.366[h]
HR 5110	F2 IV/	2.6132	6700/6000[i]	/2.6	53	1.5/0.42	43639.52
σ^2 CrB	G0 V /G0 V[b]	1.1398[b]	6030/6030[g]		21[k]		23869.390
HD 155555	G5 IV/K0 IV[c]	1.6817	5300/5200[c]		30[l]		37515.567
Z Her	F4 IV/K0 IV[d]	3.9928[f]	6580/5100[d]	1.69/2.60[d]	75[m]	1.23/1.10[d]	41111.821[f]
SZ Psc	F8 V /K1 IV[e]	3.9653[e]	6100/4800	1.50/5.48[j]	100	1.38/1.87[e]	42308.767[e]

The general data are from Nelson and Zeilik catalogue. The particular references are : a) Andersen et al.(1981) b) Bakos (1984). c) Bennett et al.(1962). d) Tümer et al. (1984). e)Jakate et al.(1976). f) Kurutao and Ibunoglu (1981). g) Calculated from Landolt-Börnstein tabulations according to spectral type adopted. h) Ludington (1978). i) Shore and Adelman (1984). j) Eaton et al.!982). k) Hoffleit (1982). l) Collier et al.(1982). m) Lacy (1982).

temperature, radius and luminosity (Vivekanada and Sarma, 1981).

– RS CVn the prototype of this class of late-type binaries, obviously shows the properties of the RS CVn group. Together with SZ Psc, RS CVn exhibits significant period variability (Hall and Kreiner, 1980) that implies uncertainties in phase calculations.

– HR 5110 is a peculiar RS CVn star. In the RS CVn class the mass ratio usually lies around unity (Hall, 1976), however, the primary component of HR 5110 is three and a half times more massive than the secondary ($M_2/M_1 = 0.28 \pm 0.08$, Conti, 1967) which fills its Roche lobe. HR 5110 looks like an Algol system with mass exchange (Dorren and Guinan, 1980) and fairly strong X-ray emission (Walter and Bowyer, 1981). Then HR 5110 would be among the more active Algol binaries. Small variations in luminosity have been observed in the light curve ($0^m.01$ at V band). This fact could be explained by a reflection phenomenon but the more likely explanation is a distortion wave (Shore and Adelman, 1984).

– The brightest component of the visual binary σ CrB is the double-lined spectroscopy binary σ^2 CrB. The two stars of the system are very similar, both have about 1 $M_\odot$, luminosity class V and spectral type near G0 (Bakos, 1984). The spectral type of the secondary is very early in comparison with typical RS CVn systems. If we should keep in mind that the RS CVn class has a common evolutionary state (Popper, 1980), σ^2 CrB would not be a RS CVn system. Recently Gimenez et al. (1986) have concluded that σ^2 is a very young star and Fekel et al. (1986) include this system in the early-type BY Dra systems.

– HD 155555 is a short period non-eclipsing spectroscopic binary and it consists of two rather similar stars, both showing Ca II emission (Stacy et al., 1980).

– Z Her is a partial-eclipsing binary. The distortion wave has not been clearly seen in its light curve, the small amplitude observed is $0^m.02 - 0^m.03$.

– SZ Psc is one of the more active RS CVn stars and one with an erratic light curve. The cooler star fills about 80–90% of its Roche lobe. This RS CVn system could be ready to begin a fast mass transfer stage, changing to a Roche-lobe filling system like an Algol binary (Hall, 1981).

Finally, it may be noticed that the evolutionary state of 13 Cet, 54 Cam and σ^2 CrB is not that commonly expected for RS CVn class: they can be included in the early-type BY Dra systems (Fekel et al., 1986).

The LWR spectra used in the present study are listed in Table 2. The observations are from IUE archives and were made with the IUE satellite from July 1979 to April 1984. All of them are high-resolution spectra taken with the long wavelength spectrograph (the resolution is about 0.2 Å, corresponding to 21.4 km s^{-1} at the spectral range of the Mg II lines).

To obtain the Mg II h and k integrated emission flux, an initial difficulty is to calculate the photospheric contribution. However, this contribution is small for cool stars and we have tried to eliminate it by extrapolating the photospheric inner line wings to the line center where the emissions occur (Blanco et al., 1974). In any event, the correction is much smaller for Mg II than for the Ca II emission (Hartmann et al., 1984).

When two emission lines are evident we have separately measured the emission from each star of the binary system. For this we have fitted the observed profile to the sum of two gaussians, one for each stellar contribution.

For 54 Cam, TY Pyx, RS CVn, HR 5110, Z Her and SZ Psc the observed fluxes (f_λ) have been transformed into stellar surface fluxes (F_λ) directly by means of stellar radius and distance. In the case of σ^2 CrB, HD 155555, 13 Cet and UX Ari the stellar radius is unknown and we have used the relationship given by Blanco et al. (1982) to obtain the surface fluxes. The adopted values for bolometric correction and apparent visual magnitude are listed in Table 3. The bolometric correction values are those

Table 2. Images from IUE data bank

Object	Image number	Observation date	Expose time min sec
13 Cet	8015	13 Jun 80	70 00
UX Ari	10244	29 Mar 81	20 00
UX Ari	11729	9 Oct 81	25 00
54 Cam	11586	19 Sep 81	35 00
TY Pyx	9689	11 Jun 81	40 00
RS CVn	10303	7 Apr 81	80 00
HR 5110	6333	8 Dec 79	15 00
HR 5110	6838	1 Feb 80	10 00
σ^2 CrB	5856	17 Oct 79	14 59
σ^2 CrB	8762	9 Sep 80	35 00
σ^2 CrB	10959	27 Jun 81	20 00
σ^2 CrB	10960	27 Jun 81	25 00
σ^2 CrB	10974	30 Jun 81	25 00
σ^2 CrB	10988	2 Jul 81	25 00
σ^2 CrB	10991	2 Jul 81	25 00
σ^2 CrB	10994	2 Jul 81	25 00
σ^2 CrB	13607	5 Jul 82	40 00
HD 155555	5044	14 Jul 79	59 59
HD 155555	11570	17 Sep 81	50 00
Z Her	10305	8 Apr 81	88 00
Z Her	11568	16 Sep 81	80 00
SZ Psc	9679	10 Jan 81	35 00

Table 3

Name	B.C. (hot/cool)	V (hot/cool)
13 Cet	/−0.42	/(7.5)
UX Ari	−0.21/−0.40	8.6/6.6
σ^2 CrB	−0.18/−0.18	6.2/6.2
HD155555	−0.27/−0.40	7.5/7.5

corresponding to spectral type. The apparent visual magnitudes for each individual component have been computed taking into account both spectral type and measured apparent visual magnitude of the whole system. In the case of 13 Cet the spectral type of the secondary is unknown and we have assumed a KV. This spectral type uncertainty implies that the obtained surface flux for 13 Cet is an upper limit of the real value. The values of surface fluxes of h and k Mg II derived are given in Table 4.

3. The surface flux F(Mg II) and its dependence on period and temperature

In our sample of RS CVn stars five systems, namely 13 Cet, RS CVn, HR 5110, SZ Psc and Z Her exhibit Mg II emission exclusively from the secondary star. For HR 5110 the cooler star is the main emission source (Simon et al., 1981). At orbital phase 0.7, near to the maximum radial velocity separation, we observe a little red asymmetry in the lines from HR 5110, which could be a small contribution from hotter star. This asymmetry would not be originated by mass transfer phenomenon (although the cooler star fills its Roche-lobe) since according to phase the asymmetry must be blue-shifted. SZ Psc shows an important blue absorption probably caused by a circumstellar envelope which has also been observed by Bopp (1981) in H_α lines. At the conjunction we have tested that the line profiles are broader than in the other studied systems, like Huenemoerder and Ramsey (1984) observed in the H_α profiles of this system. The primary emission has been observed in Z Her coming from cooler star and weak emission evident from the hotter one.

On the other hand, UX Ari, σ^2 CrB and HD 155555 exhibit two emission peaks at h and k lines, clearly seen in σ^2 CrB and HD 155555. The system σ^2 CrB can be studied in more detail because we have more images (nine). Both stars of the system show Mg II emission and there is a very good correlation between the observed velocity separation of the two peaks and that calculated from the radial velocity curve from Bakos (1984). We have two images of HD 155555 with more than two years between the Mg II observations dates. Double h and k emission lines can be seen in both images but the measured flux has changed substantially. We think that this variation may be produced by a secular variability in the stellar activity (Fernández-Figueroa et al., 1985).

We expect double emission lines from TY Pyx, as observed at Ca II H + K. The only image studied has been taken at phase 0.54 and then we are observing the end of an eclipse. At this orbital phase the relative radial velocity of the components of this system is 48 km s^{-1}, which is large enough to separate the emission from each star. However there is only one observed

Table 4. Observational data and τ/P values

Name	F_{hk} (erg cm^{-2}s^{-1})	R_{hk}	L_{MgII} (erg s^{-1})	B-V	log(τ/P)	L_X^* (erg s^{-1})
13 Cet	3.83 (6)	1.17 (-4)	1.45 (29)	0.91[a]	1.025	
UX Ari (hot)	6.57 (6)	1.05 (-4)	3.39 (29)	0.68[a]	0.328	2.089 (31)[c]
UX Ari (cool)	4.23 (6)	1.19 (-4)	2.89 (30)	0.92[b]	0.537	
54 Cam	3.83 (6)	5.73 (-5)	3.36 (29)	0.63	-0.022	5.012 (29)[d]
TY Pyx	5.76 (6)	1.25 (-4)	9.90 (29)	0.76[f]	0.745	5.190 (30)[g]
RS CVn	2.42 (6)	8.86 (-5)	3.37 (30)	0.91[h]	0.662	1.740 (31)[c]
HR 5110	1.05 (7)	1.47 (-4)	4.32 (30)	0.57[a]	0.455	1.288 (31)[c]
σ^2CrB (hot)	4.56 (6)	6.08 (-5)	3.05 (29)	0.58[a]	0.845	3.92 (30)[g]
σ^2CrB (cool)	4.71 (6)	6.28 (-5)	3.16 (29)	0.58[a]	0.845	
HD 155555 (hot)	3.67 (6)	8.20 (-5)	2.75 (29)	0.79[i]	1.053	9.84 (30)[g]
HD 155555 (cool)	2.88 (6)	6.95 (-5)	2.65 (29)	0.93[i]	1.123	
Z Her	1.72 (6)	4.48 (-5)	7.08 (29)	0.91[j]	0.742	1.995 (30)[k]
SZ Psc	1.98 (6)	6.58 (-5)	3.62 (30)	0.99[l]	0.762	2.512 (31)[c]

* Some of this values have been corrected to take into account the difference in the assumed distances.
The references are : a) Adopted values from spectral type and Landolt-Börstein tabulations. b) Hall et al.(1975) c) Walter and Bowyer (1981). d) Mangeney and Praderie (1984). f) Vivekanada and Sarma (1981). g) Walter et al. (1980). h) Popper (1961). i) Bennett et al. (1962). j) Eggen (1978). k) Vaiana et al. (1981). l) Jakate et al. (1976).

peak. It could be explained by locating the active regions on facing hemispheres and the orbit inclination. So we assumed that the observed emission come from secondary component. The absorption feature at the blue side of the line could be caused by local interstellar medium since TY Pyx lies in the zone where Vladilo et al., (1985) found Mg II interstellar absorption, and the absorption velocity is in agreement with the velocity in the LISM given by Crutcher (1982).

Initially we have plotted the surface flux of both lines ($h + k$) versus temperature (Fig. 1). If we introduce a large number of comparison stars like the sample of cool main-sequence stars studied by Hartmann et al., (1984), a general trend toward decreasing chromospheric activity, measured by F_{hk}(Mg II), can be seen for late types in both star groups (RS CVn and main-sequence stars). In the plot of R_{hk}(Mg II)($=F_{hk}$(Mg II)/$F_{\rm bol}$) given in Table 4, versus temperature (see Fig. 2), the data spread is large and it is difficult to see some tendency although the main-sequence stars continue slightly the above trend. This result has also been obtained by Blanco et al. (1982). They did not find any clear dependence between R_k values of Ca II emission K line for main-sequence stars versus effective temperature. By comparing the RS CVn systems to main-sequence stars it must be noticed that some RS CVn stars have R_{hk}(Mg II) values larger than normal cool stars, e.g. HR 5110, both components of UX Ari, TY Pyx, RS CVn and 13 Cet. However, other RS CVn have the same R_{hk} as the normal cool stars. SZ Psc and HD 155555 would be in a intermediate situation. These figures suggest the existence of two different activity levels, larger than or similar to the main-sequence stars.

A similar result can be seen in Fig. 3, where we plot R_{hk}(Mg II) versus the logarithm of rotational period. Futhermore, if the most active RS CVn systems are excluded, we obtain a trend toward decreasing activity for large rotational period. This behaviour is consistent with the general decreasing showed by main-sequence single stars (e.g. Blanco et al., 1982; Walter and Bowyer, 1981; Walter, 1981).

The dependence between R_{hk} and stellar surface gravity, g, indicates no clear influence of g on R_{hk} values. In general the activity indicators do not show dependence with the surface gravity (Walter and Bowyer, 1981).

Basri et al. (1985) have examined a sample of thiry nine late-type binaries with a range of periods larger than the used in our study. They found that the Mg II fluxes show a decrease toward larger periods. Our results are in agreement with this trend. We have found some binary systems with a cool subgiant component show activity similar to single dwarfs and dwarf binaries of comparable rotational periods. Basri et al. (1985) with a large sample extending over a much larger range in periods conclude that the synchronized binaries with cool subgiants are more active than single dwarfs with the same rotation period. From their Fig. 2 it is evident that, for $P < 10^d$, there are single dwarfs, and dwarfs in binaries, with Mg II surface fluxes comparable to those of the subgiant-containing systems. Given that the binaries with cool subgiants in our sample have rotation periods shorter than 10^d our data are in agreement with the conclusions of Basri et al.

4. Relation of R_{hk} to the inverse Rossby number

The Rossby number is an important parameter in dynamo theories for magnetic field generation. Noyes et al. (1984) suggested that chromospheric activity depends on this parameter P/τ, where P is the rotational period and τ is the turnover time of convective cells. The relation of R_{hk} to the inverse Rossby number has been studied in normal stars by Hartmann et al. (1984). They found a general behaviour for main-sequence late type stars in the range $0.5 < \tau/P < 3.2$. Later the analysis of W UMa-type binaries carried out by Rucinski (1985) showed

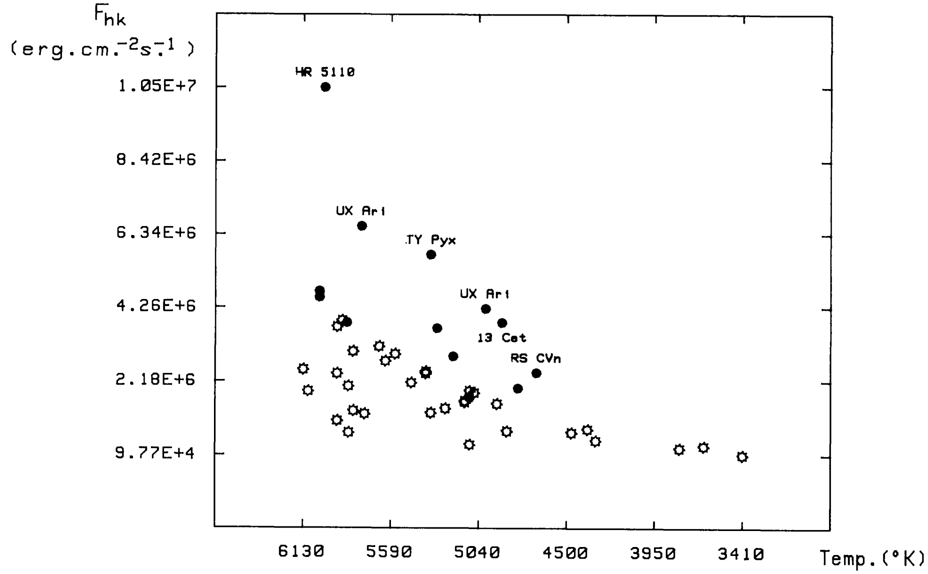

Fig. 1 Surface flux in h and k lines versus effective temperature. Open circles are Hartmann et al. main-sequence stars and filled circles are RS CVn systems (this paper)

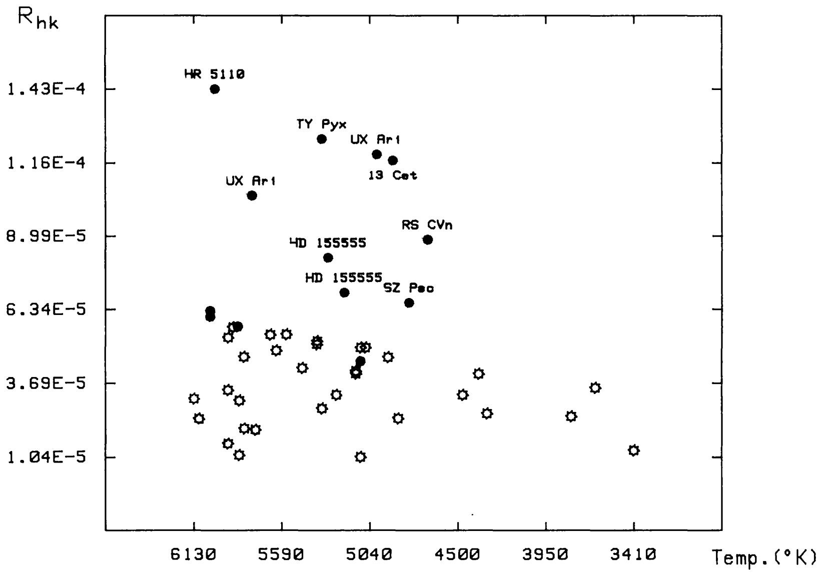

Fig. 2. Fluxes in h and k lines normalized to bolometric flux vs. effective temperature. Symbols are the same that in Fig. 1

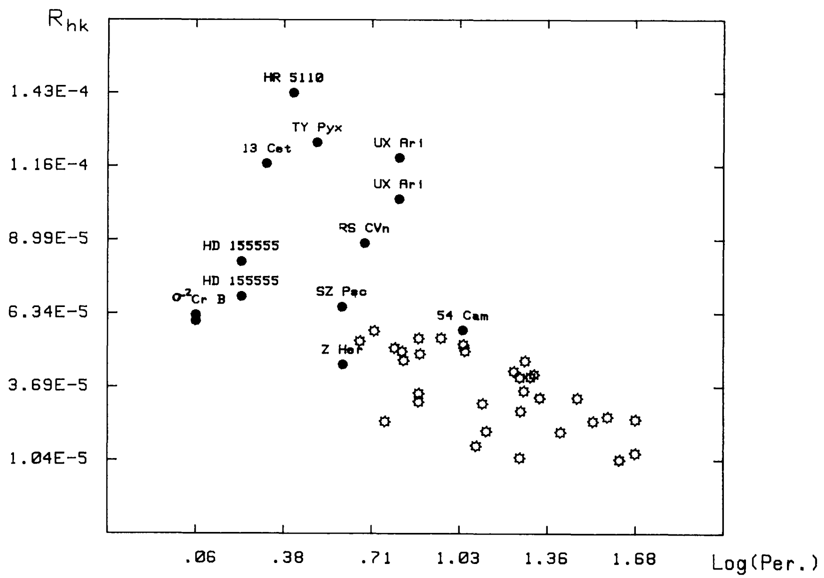

Fig. 3. R_{hk} vs. logarithm of rotational period. Symbols are the same that in Fig. 1

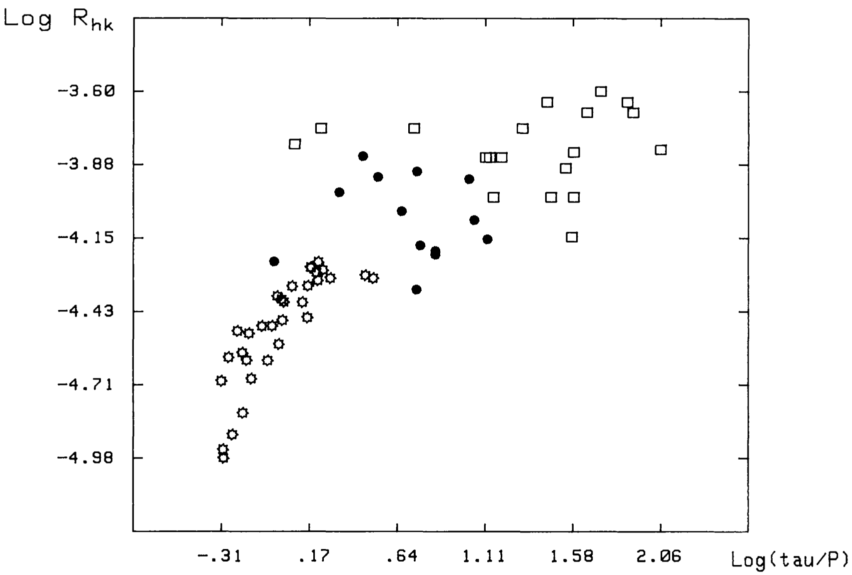

Fig. 4. Relation between Mg II activity to the inverse Rossby number. Open circles are the Hartmann et al. stars, squares are Rucinski's set of W UMa stars and filled circles are our RS CVn systems

roughly an extension of this dependence essentially in the range $12.6 < \tau/P < 125$.

We have searched for a relation between R_{hk} and the inverse Rossby number in the RS CVn systems analysed in this paper. The adopted τ/P values are derived from the relationships with the $(B-V)$ index reported by Noyes et al. (1984) and are listed in Table 4. The τ/P values of the RS CVn systems cover the range $3.2 < \tau/P < 12.6$ filling the gap between the Hartmann et al. and Rucinski data. In Fig. 4 we plot $\log(R_{hk})$ versus $\log(\tau/P)$ for the Hartmann et al. main-sequence stars, Rucinski W UMa-type stars and our RS CVn binaries. Our data give a large scatter analogous to obtained by Rucinski, but are consistent with these previous works. For $\tau/P > 3.2$ we can fit a straight line consistent with the Rucinski data of the form

$$\log(R_{hk}) = 0.347 \log(\tau/P) - 4.33$$

In order to evaluate the influence of evolutionary state we can only use the data published by Gilliland (1985), which showed that the value of τ can changes during the star evolution even into the main-sequence stage. The maximum variation of τ with Gilliland data is a factor of 3, that implies a change of ± 0.7 in the abcissa of Fig. 4. We conclude that there is a general relation between R_{hk} and τ/P, but the data uncertainties prevent a more detail examination of this relation according to each stellar group.

5. Relation between chromospheric and coronal activity

The survey in X-rays from Walter et al. (1980), Walter and Bowyer (1981), Vaiana et al. (1981) and Walter (1982) gives us the values of X-ray flux for some RS CVns (Table 4). These are integrated values of whole system and so we have considered total luminosities when two Mg II emissions were measured. The comparison of L(Mg II) and L_x is shown in Fig. 5. A clear correlation between X-ray and Mg II emission can be seen. This correlation seems also consistent with the scaling law of normal slowly rotating stars, $R(X)$ $R(\mathrm{Mg\,II})^3$ (Ayres et al., 1981), but it is difficult to solidify this point with present observations. Simultaneous Mg II and X-ray observations are required to clarify the RS CVn behaviour.

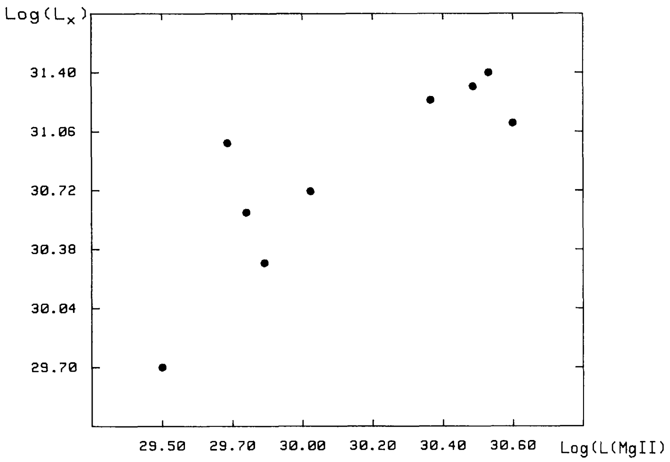

Fig. 5. X-ray luminosity vs. Mg II $h+k$ luminosity. There is a good correlation, although HD 155555 have a small X-ray over-luminosity

6. Final remarks

In this paper we have undertaken a comparative study of RS CVn systems selected from Hall's (1976) list by means of IUE high resolution spectra. We have searched for the existence of double Mg II emission from each system, finding some systems with two active stars, some with only one activity source and systems with one clear emission and other possible one.

We conclude for this RS CVn sample that no clear dependence exists between the Mg II chromospheric activity and photospheric temperature or surface gravity. However, a tendency of this activity to decrease is found when the rotational period increase. By comparison with the chromospheric activity in main-sequence late-type stars, the existence of two activity levels is suggested, one more active than the main-sequence sample and the other with similar activity levels.

About the relation of R_{hk} to the inverse Rossby number, our RS CVn stars complement previous works carried out by Hartmann et al. (1984) and Rucinski (1985). A general relation between these two parameters has been found. The RS CVn stars fill the gap found by Rucinski between W UMa and the main-sequence stars.

A significant correlation exists between the X-ray emission L_x and the chromospheric emission $L(\mathrm{Mg\,II})$. However, it will be necessary to obtain simultaneous Mg II and X-ray observations for a better determination of this dependence.

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